

Review

# Environmental Performance of Emerging Photovoltaic Technologies: Assessment of the Status Quo and Future Prospects Based on a Meta-Analysis of Life-Cycle Assessment Studies

Steffi Weyand <sup>1,\*</sup> , Carolin Wittich <sup>2,3</sup> and Liselotte Schebek <sup>1</sup>

<sup>1</sup> Chair of Material Flow Management and Resource Economy, Institute IWAR, Technische Universität Darmstadt, Franziska-Braun-Strasse 7, 64287 Darmstadt, Germany; l.schebek@iwar.tu-darmstadt.de

<sup>2</sup> Chair of Geomaterial Science, Institute of Applied Geosciences (IAG), Technische Universität Darmstadt, Alarich-Weiss-Straße 2, 64287 Darmstadt, Germany

<sup>3</sup> Chair of Surface Science, Materials Science Department, Technische Universität Darmstadt, Otto-Berndt-Str. 3, 64287 Darmstadt, Germany

\* Correspondence: s.veyand@iwar.tu-darmstadt.de; Tel.: +49-6151-16-20730

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**Abstract:** Emerging photovoltaic technologies are expected to have lower environmental impacts during their life cycle due to their extremely thin-film technology and resulting material savings. The environmental impacts of four emerging photovoltaics were investigated based on a meta-analysis of life-cycle assessment (LCA) studies, comprising a systematic review and harmonization approach of five key indicators to describe the environmental status quo and future prospects. The status quo was analyzed based on a material-related functional unit of 1 watt-peak of the photovoltaic cell. For future prospects, the functional unit of 1 kWh of generated electricity was used, including assumptions on the use phase, notably on the lifetime. The results of the status quo show that organic photovoltaic technology is the most mature emerging photovoltaic technology with a competitive environmental performance, while perovskites have a low performance, attributed to the early stage of development and inefficient manufacturing on the laboratory scale. The results of future prospects identified improvements of efficiency, lifetime, and manufacturing with regard to environmental performance based on sensitivity and scenario analyses. The developed harmonization approach supports the use of LCA in the early stages of technology development in a structured way to reduce uncertainty and extract significant information during development.

**Keywords:** Meta-analysis; harmonization; life-cycle assessment; perovskite solar cell; organic photovoltaic; emerging technology

## 1. Introduction

Renewable electricity generation technologies—wind, solar, and water—induce very low greenhouse gas (GHG) emissions in their use phase. However, it is well known that upstream processes—extraction of raw materials, production of materials and components, transportation, and manufacturing—consume significant amounts of energy and contribute to GHG emissions and other environmental impacts. For a comprehensive assessment of environmental performance, the full life cycle of production, use, and end-of-life has to be taken into account. The method of life-cycle assessment (LCA) [1,2] is widely used for investigation of the life-cycle impacts of conventional and renewable electricity generation technologies.

Today, a great amount of interest exists in the so-called emerging or third-generation photovoltaic technologies (PV). These comprise dye-sensitized solar cells (DSSC), organic photovoltaics (OPV), perovskite solar cells (PSC), quantum-dot photovoltaics (QDPV), and inorganic cells such as the copper–zinc–tin–sulfur–selenide solar cells (CZTSSe) [3]. Their common unique feature is the extremely thin-film technology which enables easy and fast manufacturing, for example, in the form of printing methods [4–7]. From the environmental point of view, emerging PVs are of interest since their thin-film technology is associated with savings of weight and materials. Therefore, the life-cycle impacts of emerging PVs are expected to be lower than those of commercial PVs of the first and second generations.

PVs were investigated in a multitude of LCA studies which led to general insight into their life-cycle impacts [8–15], i.e., about 80% of total life-cycle GHG emissions can be attributed to the production stage [15]. However, different LCA studies on PV revealed large differences in results [11,12], an observation that was also made for LCAs of other electricity generation technologies. This finding obviously compromises the use of LCA for decision support in technology development, as well as in the field of energy policy, since the results are associated with high uncertainty. The reasons for these differences were shown to be legitimate, due to the deviating methodologies, as well as differences and inconsistencies in the technological parameters and assumptions of the respective studies [16]. To tackle this problem, meta-analyses are a suitable means to derive more substantiated results from LCA studies through the combination of a systematic review and the development of technology-specific harmonization approaches. In the field of electricity generation technologies, meta-analyses were conducted and harmonization approaches were developed for first- and second-generation PVs [11,12], concentrating solar power [17], wind power [18], nuclear power [19], and coal-fired power plants [20].

In the case of PV, notably, the two meta-analyses of [11,12] provided a systematic review and harmonization approach, shedding light on the contribution of specific parameters to deviations of studies and reducing deviations of life-cycle impacts [11,12]. However, both meta-analyses exclusively comprised crystalline silicon PVs of the first generation and thin-film technologies of the second generation. In addition, these studies were restricted to GHG emissions in terms of environmental impacts. Consequently, the influences of materials on further impact categories, such as resource depletion and toxicity indicators, were not considered. In view of the fact that material systems for various types of current PVs, notably emerging PVs, largely differ, the identification of possible tradeoffs between impacts is important information from LCA, which requires the inclusion of further impact categories.

With respect to emerging PVs, several LCA studies were conducted [21–43]; however, until now, no comprehensive meta-analysis was performed. Given the high expectations of emerging PVs, thorough and reliable LCA results are crucial. In this study, a meta-analysis of LCAs on emerging PVs is presented, aiming at both the assessment of the current stage of development and possible future prospects. The meta-analysis comprises a systematic review and harmonization of LCA studies and datasets on emerging PVs. The results of this meta-analysis are used to characterize the status quo of environmental performance of emerging PVs with respect to GHG emissions and possible tradeoffs, and to investigate the influencing factors of possible future performance in comparison with first- and second-generation PVs.

## 2. Methodology

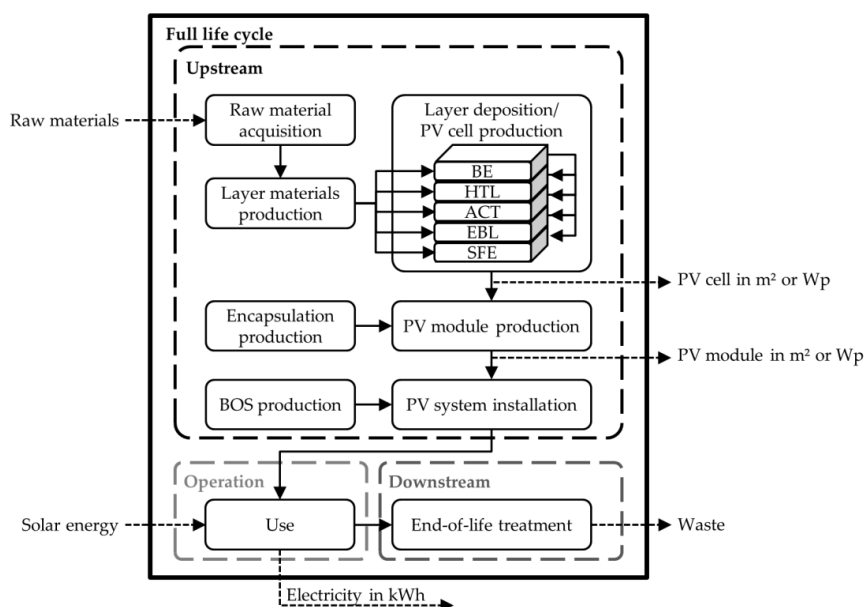
### 2.1. Overview

As a first step, based on the general methodology of LCA, the technological life cycle of PV is described. From this description, the relevant parameters and characteristics of PV can be derived, which are then evaluated by means of this meta-analysis. Secondly, a systematic review of the literature is performed, from which, according to defined criteria, studies and datasets are selected for inclusion. Finally, the harmonization approach is presented, covering a consistent reference unit for the comparison of LCA results, key indicators, and key modeling assumptions.

## 2.2. Conceptual Life Cycle of Emerging PVs

### 2.2.1. Description of the Technological Life Cycle of Emerging PVs

The life cycle of emerging PVs can be divided into upstream, operation, and downstream stages, as shown in Figure 1. The upstream stage refers to the raw material acquisition, consisting of the extraction and processing of raw materials. The raw materials are processed to layer materials. The conceptual solar cell configuration of emerging PVs is composed of five layers: the substrate with front electrode, electron blocking layer, active layer, hole transport material, and back electrode. The layer materials and deposition methods differ considerably; an overview of the most frequently applied materials is given in Table 1. After the PV cell production, the PV cells are interconnected and encapsulated to form a PV module. The PV system of emerging PVs, consisting of the PV module and the balance-of-system (BOS), covers a wider product variety than the first- and second-generation PVs, ranging from a typical rooftop module to building-integrated products or personal gadgets such as mobile chargers or OPV lamps. Consequently, the BOS components vary as well, and they may comprise not only wires and inverters but also Universal Serial Bus (USB) ports or plastic cases.



**Figure 1.** Conceptual life cycle of emerging photovoltaic technologies (PVs) with the technological components and methodological elements such as life-cycle stages, processes, functional units, and input/output flows.

After the installation or distribution of the PV system, its operation or use stage starts. In this stage, impacts only occur during the maintenance, repair, and replacement of PV modules or components. For first- and second-generation PVs, these impacts are very low and negligible [15]. For emerging PVs, there are no data on these impacts, which are expected to be higher due to the shorter lifetime at present. The maximum measured lifetime of emerging PVs ranges from less than one year for QDPV and PSC [44,45] to around seven years for OPV [46]. For DSSC, no data were found. In contrast, first- and second-gen PVs show a lifetime of up to 30 yrs. However, the lifetime of emerging PVs was obtained from laboratory or pilot applications, and it is expected to increase in future.

The downstream stage refers to the end-of-life treatment. For emerging PVs, the end-of-life treatment is not known yet, since there are hardly any PV products available which incorporated emerging PV materials. According to the Waste of Electrical and Electronic Equipment Directive specifying the general requirements for electronic waste in the European Union (EU) [47], end-of-life treatments should comprise recovering or recycling. However, at present, large amounts of electronic products and waste are still landfilled globally; thus, disposal in a landfill has to be considered as well.

**Table 1.** Overview of the layer materials and deposition methods of emerging photovoltaic technologies (PVs; summarized from life-cycle assessment (LCA) literature); in bold, the most assessed materials and deposition methods of each layer (with frequency) are shown.

Layer	DSSC	OPV	PSC	QDPV	DSSC	OPV	PSC	QDPV
	Materials				Deposition Methods			
BE	<b>FTO + Ag (3)</b>	<b>Ag (40)</b> , Al, Al+Ca, Al+Cr, C	<b>Au (12)</b> , Al or MoOx/Al, Pt, Ag, or C	<b>ITO (1)</b>	[21]	<b>Screen printing</b> , Gravure printing, N/A, Slot die coating, Evaporation, Sputtering	<b>Evaporation</b> , Dip coating, Sputtering	[41]
HTL	<b>Electrolyt (porphyrin-Co- dye) (3)</b>	<b>PEDOT:PSS (37)</b> , -, MoO <sub>3</sub> , TiOx	<b>Spiro-OMeTAD (14)</b> , PCBM, Electrolyt (LiI), CuSCN or -	<b>Al<sub>2</sub>O<sub>3</sub> (1)</b>	[21]	N/A, Slot die coating, Screen printing, Gravure printing, Evaporation	<b>Spray coating</b> , Screen printing, Sputtering, N/A	[41]
ACT	<b>Ru-dye (3)</b>	<b>P3HT:PCBM (45)</b> , combination of P3HT or PCBM and other acceptor or donator	<b>CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub>-ICl<sub>2</sub>, -I<sub>2</sub>Cl (16)</b> , CH <sub>3</sub> NH <sub>3</sub> SnI <sub>3-x</sub> Br <sub>x</sub> , CsPbBr <sub>3</sub> , FAPbI <sub>3</sub>	<b>CdSe (1)</b>	[21]	<b>Slot die coating</b> , Gravure printing, Evaporation, N/A, Spin coating, Inkjet printing	<b>Spin coating</b> , Dip coating, Evaporation, Slot die coating, Spray coating	[41]
EBL	<b>TiO<sub>2</sub> (3)</b>	<b>ZnO (21)</b> , PEDOT:PSS, PEDOT:PSS + ZnO, MoO <sub>3</sub> , MeOH+ZnO, Ag	<b>TiO<sub>2</sub> (Comp., Meso.) (16)</b> , SnO <sub>2</sub> , PEDOT:PSS, ZnO	-	[21]	<b>Slot die coating</b> , Gravure printing, Screen printing, N/A, Inkjet printing, Spin coating	<b>Spin coating</b> , Spray coating/pyrolysi, Screen printing, -N/A, Sputtering	[41]
FE	<b>Pt + Ag (3)</b>	<b>ITO (19)</b> , Ag, Ag + PEDOT:PSS, PEDOT:PSS, FTO, -, C, Al, Cu	<b>FTO (19)</b> , ITO	-	[21]	<b>Inkjet printing</b> , Sputtering, Screen printing, Slot die coating, Patterning, N/A	N/A, Evaporation, Patterning, Anti-reflex-coating, Sputtering	[41]
S	<b>Glass (2)</b> , PET	<b>PET, PET + UV-Filter, Barrier (63)</b> , Filter, -, Glass	<b>Glass (21)</b> , PET	<b>Al (1)</b>	[21]	N/A	N/A	[41]

S: substrate; FE: front electrode; EBL: electron blocking layer; ACT: active layer; HTL: hole transport layer; BE: back electrode; DSSC: dye-sensitized solar cells; OPV: organic photovoltaics; PSC: perovskite solar cells; QDPV: quantum-dot photovoltaics (QDPV).

### 2.2.2. Methodological Elements of LCA of Emerging PVs

The assessment of life-cycle impacts follows the LCA method of the ISO standards 14040/14044 [1,2]. According to these standards, the life-cycle impacts are assessed based on the modeled life cycle, the so-called product system, and they are quantified per impact category indicator in relation to the so-called functional unit of the product system. Whereas the functional unit is the quantifier of the function of the product system, used as a reference unit in LCA, the impact category indicator is the quantifier of the impact category. The considered impact categories are selected depending on the potential environmental impacts and the goal of the LCA study. In this meta-analysis, the life-cycle impacts are used to describe the environmental performance of emerging PVs.

In LCAs of PVs in general, the product system is the modeled PV system, encompassing the components of PV cells, PV modules, and BOS, as well as the considered life-cycle stages in terms of the defined system boundaries (upstream, operation, and downstream stage) and the corresponding processes (Figure 1). In contrast to first- and second-generation PVs, the LCAs of emerging PVs do not always assess the full life cycle, but only part of it. Depending on the product system, three functional units are possible for emerging PVs and for PVs in general [48]. Firstly, the functional unit of area, usually  $1 \text{ m}^2$ , can be used for the comparison of PV cells or PV modules with the same efficiency. Secondly, in the case of emerging PVs with various efficiencies, the functional unit of 1 watt-peak ( $W_p$ ) should be used for meaningful results. This functional unit is known as the nominal power and takes into account the maximum efficiency of the PV cell or PV module under standard test conditions, which are a light intensity of  $1000 \text{ W/m}^2$ , cell temperature of  $25^\circ\text{C}$ , and air mass of 1.5, according to the standard IEC 61215 of the International Electrochemical Commission [49]. Third, the functional unit of 1 kWh of electricity fed into the grid is typically used for a mature electricity generation technology installed on an industrial scale. The latter is the only functional unit that enables the inclusion of the operation stage (Figure 1). During the life cycle of emerging PVs, on one hand, the potential environmental impact results from the upstream energy inputs of the layer deposition and the production of the PV cell, PV module, and PV system in relation to the energy output during the use phase, and the inputs or outputs during the end-of-life treatment. This results in the use of energy and corresponding GHG emissions. On the other hand, there are impacts resulting from the layer materials, occurring mostly in the upstream and downstream stages due to the material acquisition or end-of-life treatment. During the use stage, these materials are connected and encapsulated to form the final products and, thus, do not come into direct contact with the environment in LCA studies. In LCA studies, the impacts of these materials may contribute to tradeoffs with respect to resource depletion or toxicity impacts.

## 2.3. Systematic Review Approach of LCA Literature and Datasets

### 2.3.1. Literature and Dataset Search

The systematic review covered literature references, i.e., publications and datasets of LCAs on emerging PVs, from literature databases and the openLCA Nexus repository. The literature search was carried out using four literature databases: Web of Science, Wiley online library, ScienceDirect, and SciFinder. Here, combinations of the following keywords were used: life-cycle assessment, dye-sensitized solar cell, organic photovoltaic, perovskite solar cell, quantum-dot photovoltaic, and copper–zinc–tin–sulfur–selenide solar cell. Further considered synonyms are listed in Table S1 (Supplementary Materials). The search strategy focused exclusively on full journal articles. The identified literature references were published between 2001 and 2018.

The openLCA Nexus repository provides more than 130,000 LCA datasets of 20 LCA databases, including well-known LCA databases such as ecoinvent, GaBi LCA Database, and European reference Life Cycle Database (ELCD; last access: 29 January 2019). However, this repository did not include any LCA dataset for the previously used keywords.

### 2.3.2. Literature and Dataset Selection

The identified literature references were primarily screened, and suitable LCA studies and datasets were selected for inclusion in this meta-analysis. The following inclusion criteria were applied:

- Relevance of the technologies: Only emerging PVs from the fields of DSSC, OPV, PSC, QDPV, and CTZSSe were considered in this meta-analysis.
- Quality and relevance of the LCA study: The underlying LCA study of a literature reference had to be in compliance with the ISO 14040/14044 standards [1,2].
- Completeness and transparency of the LCA study: In this meta-analysis, as a minimum requirement, the product system needed to consider at least the upstream impacts of PV cells (Figure 1). Transparency had to be ensured with respect to basic LCA elements, such as the defined goal with the corresponding information on the functional unit and assessed impact categories.

The primary screening resulted in 28 LCA studies (three DSSC, 16 OPV, eight PSC, one QDPV, and zero CTZSSe) on the considered emerging PVs. In most LCA studies, different layer materials, deposition methods, and end-of-life-treatments were analyzed, resulting in more than one LCA dataset per LCA study. Therefore, the 28 LCA studies were further subdivided into 134 LCA datasets. The following secondary inclusion criteria were applied to select suitable LCA datasets:

- (1) The LCA dataset was not published previously in another LCA study.
- (2) The LCA dataset included, as a minimum life cycle, impacts of the energy demand or the contributed GHG emissions of the production of PV cells.
- (3) The LCA dataset included information necessary for the conversion of the functional unit to  $\text{m}^2$ ,  $\text{W}_p$ , or kWh.

Finally, a total number of 22 LCA studies (three DSSC, 67 OPV, 23 PSC, and one QDPV) and 94 LCA datasets were included in this meta-analysis. The excluded LCA datasets are summarized in Table S2 (Supplementary Materials). For CTZSSe, no relevant LCA dataset was found. Therefore, this emerging PV was excluded from this meta-analysis.

## 2.4. Harmonization Approach for LCA Datasets

### 2.4.1. General Framework

The methodology for harmonization was based on the approach of [11,12], which was conceptually designed for first- and second-generation PVs. Their general framework for harmonizing LCA results for PV is described by Equation (1).

$$\text{GHG} = W / (I \cdot \eta \cdot \text{PR} \cdot \tau \cdot A), \quad (1)$$

where GHG stands for the GHG emissions in g  $\text{CO}_2$ -equivalent (eq) per functional unit of 1 kWh, W refers to the total GHG emitted over the life cycle in g  $\text{CO}_2$ -eq, I is the irradiation in  $\text{kWh}/(\text{m}^2 \cdot \text{year})$ ,  $\eta$  is the efficiency as a percentage, PR is the performance ratio of PV systems as a percentage,  $\tau$  is the lifetime in years, and A is the total module area in  $\text{m}^2$ .

Based on this equation, two levels of harmonization were discerned in [11,12]. The first level involves an in-depth investigation of the underlying LCA studies in terms of the alignment of the total GHG impacts with a consistent life cycle, i.e., including or excluding components and life-cycle stages in or from the numerator W. The second level is less resource-intensive and includes only the harmonization of the GHG impacts according to Equation (1). Whereas both levels were applied in [12], the harmonization approach of [11] was exclusively restricted to the second level, i.e., no alignment of W, whereby standard values of I,  $\eta$ , PR, and  $\tau$  were defined and the GHG impacts were harmonized to these standard values using a developed spreadsheet-based meta-model.

In this meta-analysis, the harmonization approach encompassed the second level of the definition of the standard values of PR, I,  $\eta$ , and  $\tau$  as a consistent set, which is generally necessary for the



characterization of any PV technology. However, from the systematic review, three requirements were identified to widen the approach of [11] regarding emerging PVs. Firstly, different functional units were found in the LCA datasets on emerging PVs, resulting in additional harmonization to a consistent functional unit. Secondly, the scope of the environmental impacts was widened to include further key indicators in order to account for impacts related to the specific layer materials. Thirdly, to substantiate the comparison of results from the LCA datasets, the consideration of additional methodological specifications was necessary, such as the diverging state of technology development and life-cycle information related to the first level of the harmonization [12]. This information was analyzed in terms of qualitative factors. These requirements resulted in the framework conditions described below for harmonizing LCA results on emerging PVs.

#### 2.4.2. Harmonization to Consistent Functional Units

The LCA datasets on emerging PVs were related to the three definitions of the functional unit: energy, rated power, and area. The rationale behind these definitions of the functional unit was as follows: The comparison of first- and second-generation PVs with each other or with further energy technologies was based on the typical functional unit of 1 kWh of electricity fed into the grid. Accordingly, the functional unit reported for LCA of first- and second-generation PVs in [11,12] was exclusively defined as 1 kWh of electricity fed into the grid. For the comparison of emerging PVs with first- and second-generation PVs, this functional unit was used as well. However, the choice of the functional unit of energy necessarily requires data on module efficiencies, transmission losses in terms of the performance ratio, location-specific irradiation, and lifetime of the PV systems [48]. As a result, notable assumptions on prospective applications and expected lifetime of emerging PVs are mandatory for the calculation. However, at this development stage, there is hardly any knowledge about these applications and the expected lifetime. Therefore, many LCA studies on emerging PVs did not include such highly speculative assumptions and restricted their research question to investigation of the current production of PV cells or PV modules in laboratories or in pilot plants, as well as using the functional units of area or rated power (Figure 1). Accordingly, the definition of the functional unit depends on the research question or goal of the LCA study.

In this meta-analysis, two research questions (hereafter termed as cases) were investigated and resulted in different functional units per case, which were investigated by means of the harmonized results. Firstly, for the case “characterizing the status quo of environmental performance of emerging PVs”, the functional unit of 1  $W_p$  provided PV cell, module or system was used. Secondly, for the case of a substantiated discussion on the “possible future environmental performance” in view of a comparison with first- and second-generation PVs, the functional unit was 1 kWh of generated electricity.

#### 2.4.3. Key Indicators (KEYIs)

The key indicators, hereinafter referred to as KEYIs, are the impact category indicators that were selected for a comprehensive description of the potential environmental impacts of the considered emerging PVs and in general for the comparison of PVs. Considering the aforementioned potential environmental impacts, the following five KEYIs were selected for the assessment of the life-cycle impacts, divided into energy-related and material-related KEYIs for the tradeoff consideration:

##### 1. Energy-related KEYIs:

- Cumulative energy demand (CED): The CED in MJ PE quantifies the primary energy (PE) inputs of the included life cycle stages.
- Global warming potential (GWP): GWP quantifies the GHG emissions in g of carbon dioxide equivalents (g CO<sub>2</sub>-eq) resulting mostly from the energy demand.

##### 2. Material-related KEYIs:

- Resource depletion, mineral, fossil, and renewable resources (RDPf): The RDPf in g of antimony equivalents (g Sb-eq) considers the resource use and impacts on the resource availability.
- Toxicity indicators: These indicators are relevant in assessing the toxicity potential of the included layer materials to the ecosystem and human health, assessed by the following two indicators in this meta-analysis:
  - Ecotoxicity potential for freshwater (ETPf) in comparative toxic units for ecosystems (CTUe);
  - Human toxicity, cancer effects (HTPc) in comparative toxic units for human health impact equivalent to the incidence of cancer (CTUh).

In [50], the consideration of more tradeoffs was highlighted, such as land use or eutrophication. However, for the comparison of emerging PVs, the data coverage is not sufficient (see File S1, Supplementary Materials). Furthermore, the five KEYIs cover the most important tradeoffs for the comparison of PV technologies. Further tradeoff considerations may be important in the case of a comparison with further energy generation technologies. For this case, the harmonization approach is extendable to further impact indicators beyond these five introduced KEYIs.

#### 2.4.4. Key Modeling Assumptions (KEYAs)

The key modeling assumptions, hereinafter referred to as KEYAs, summarize methodological specifications that may influence the total life-cycle impacts of emerging PVs:

1. LCA type, temporal coverage, and technology scale: These KEYAs were interrelated in LCA studies on emerging PVs. The term LCA type stands here for the modeling approach of the LCA study. It was differentiated into the following:
  - Conventional LCA, representing the common approach of LCA studies, particularly commercial technologies which are established on the market and show sufficient primary data quantities for the assessment of the status quo;
  - Prospective LCA/ex ante LCA, representing an approach particularly for the assessment of emerging technologies to assess their prospective developments in comparison with commercial technologies [51,52].

Accordingly, the temporal coverage of a conventional LCA is based on present conditions of technologies, whereas prospective LCAs consider future scenarios and developments of technologies. Moreover, the technology scale of the assessed technology depends on the LCA type as well. The technology scale characterizes here the stage of development of the assessed emerging PV, and it is an important specification for the characterization and differentiation of emerging PVs in LCA studies. In conventional LCAs, technologies are assessed based on the current technology scale and stage of development. On the contrary, in prospective LCAs, the technology scale is upscaled by the consideration of likely future scenarios and, consequently, emerging technologies are assessed based on higher technology scales. In particular, for a fair comparison between emerging PVs and commercial technologies or technologies at higher or lower development stage, the technology scale of the assessed technology needs to be indicated. A common method for characterizing the technology scale is the concept of technology readiness levels (TRLs), consisting of nine TRLs established by National Aeronautics and Space Administration (NASA) [53]. However, none of the included LCA studies reported TRLs. Therefore, the following classification scheme based on the TRL concept was introduced and applied for the characterization of the technology scale of the LCA datasets on emerging PVs:



- TRL 1 (“basic principles observed and reported”) was omitted since it may be relevant for LCA studies of new technology concepts but not for the included emerging PVs [53];
  - Laboratory scale, referring to TRLs 2–4 (“research to prove feasibility”);
  - Pilot scale, referring to TRLs 5–7 (“technology demonstration”);
  - Industrial scale, referring to TRLs 8–9 (“system test, launch, and operations”).
2. Product system: The considered product system of emerging PVs can be distinguished into the three options: (1) PV cell, (2) PV module, and (3) PV system. As shown in Figure 1, the PV system includes more components than the PV cell. Each component has its own impact and, consequently, the consideration of its contributions and tradeoffs is necessary.
  3. Layer components: The different layer options as components of the PV cell are relevant to the life-cycle impacts resulting from the energy requirements of the deposition and from possible hazardous elements or materials. Therefore, the further subdivision of the PV cell into the layer components is necessary to track and compare the life-cycle impacts and the contribution of the layer materials and deposition methods.
  4. System boundary: As mentioned above, the minimum requirement for the selection of a dataset was the inclusion of the upstream stage, i.e., the production of the PV cell. In addition, studies could also include also the operation stage or cover the full life cycle, including the downstream stage. While the inclusion of the operation stage yields electricity generation and, thus, is covered by the respective functional units of energy, the inclusion of the downstream stage is often omitted and hinders the comparison of results. However, since the LCA studies gave very limited information on end-of-life treatment, the contribution of the downstream stage could not be added to the overall result; thus, an important source of tradeoff was not fully considered. Therefore, the influence of the system boundary was taken into account as KEYAs.

#### 2.4.5. Key Performance Parameters (KEYPs)

The key performance parameters, hereinafter referred to as KEYPs, characterize the performance of the PV system, and they were significant for the determination of the maximum electricity yield during the operation stage. The KEYPs were as follows:

1. Efficiency of the PV cell or PV module ( $\eta$ );
2. Performance ratio of the PV system (PR);
3. Irradiation on the installed PV system (I);
4. Lifetime of the PV system ( $\tau$ ) and its components.

### 3. Results

#### 3.1. Systematic Review of LCA Datasets on Emerging PVs

The 22 reviewed LCA studies with the number of respective LCA datasets are given in Table 2, along with information on the functional units, KEYIs, KEYAs, and KEYPs. For each LCA dataset, the considered KEYIs were specified; CED was the most commonly considered KEYI, with 67 of the 94 LCA datasets considered; GWP was the second most widely considered KEYI, with 59 LCA datasets considered. RDPf and the two toxicity indicators were assessed for almost all LCA datasets on PSC. However, for the other emerging PVs, these KEYIs were only considered in three LCA studies, with 8–11 LCA datasets on OPV and none on DSSC and QDPV considered. For OPV, 67 LCA datasets from 14 LCA studies could be selected and, for PSC, 23 LCA datasets from six LCA studies could be selected. However, for DSSC and QDPV, only one LCA study with three and one LCA datasets, respectively, could be found.

**Table 2.** Reviewed LCA studies with number of data sets on DSSC, OPV, PSC, and QDPV (22 studies, 94 LCA datasets), considered key indicators (KEYIs) with corresponding functional unit, key modeling assumptions (KEYAs) and assumptions on the four key performance parameters (KEYPs).

LCA Studies with Number of Included LCA Data Sets		KEYIs <sup>a</sup>				KEYAs <sup>b</sup>				KEYPs <sup>c</sup>			
Author (Year)	DS	FU	CED	GWP	RDPf/Tox	LCA type/TS	PS	SB		$\eta_R$	$\tau_R$	$I_R$	$PR_R$
			<i>in MJ PE</i>	<i>in g CO<sub>2</sub>-eq</i>	<i>in g Sb-eq or CTU</i>			<i>Down-stream</i>		<i>in %</i>	<i>in years</i>	<i>in kWh/m<sup>2</sup>-year</i>	<i>in %</i>
DSSC													
Parisi et al. (2014) [21]	3	1 kWh	✓	✓	–/–	P	PI	S	□	8	20	1700	75
OPV													
Anctil et al. (2013) [22]	13	1 W <sub>p</sub>	✓	–	–/–	C	L	M	□	3.0–7.7	N/A	N/A	N/A
Darling and You (2013) [54]	1	1 m <sup>2</sup>	✓	–	–/–	C	PI	M	□	1	2	1700	75
Espinosa et al. (2011a) [23]	1	1 m <sup>2</sup>	✓	✓	–/–	C	IN	M	□	2	15	1700	80
Espinosa et al. (2011b) [24]	1	104 cm <sup>2</sup>	✓	–	–/–	C	IN	S	□	2–3	2	N/A	N/A
Espinosa et al. (2012a) [25]	1	1 m <sup>2</sup>	✓	✓	–/–	P	PI	M	□	1	15	1700	80
Espinosa et al. (2012b) [26]	10	1 m <sup>2</sup>	✓	–	–/–	C	PI	M	□	1	15	1700	N/A
Espinosa et al. (2013) [27]	6	1 m <sup>2</sup>	✓	–✓	–✓/–	C	PI	M	□	2	N/A	1700	N/A
Espinosa et al. (2014) [28]	5	1 m <sup>2</sup>	✓	–	–/–	C	IN	M/S	□	2.2/1.6	1	1700	80
Espinosa et al. (2016) [29]	8	1 kWh	–	✓	✓/✓	C	PI	M	■	0.7–1	2	–	N/A
García-Valverde et al. (2010) [30]	1	1 m <sup>2</sup>	✓	✓	–/–	C	L	M	□	5	15	1700	80
Roes et al. (2009) [31]	2	1 W <sub>p</sub>	✓	✓	✓/–	C	L	S	□	5	25	1700	75
Søndergaard et al. (2014) [32]	3	1 m <sup>2</sup>	✓	–	–/–	C	PI	M	■	2	N/A	1700	80
Tsang et al. (2015) [33]	3	1 W <sub>p</sub>	✓	✓	–/–	P	PI	C	□	5	N/A	1700	75
Tsang et al. (2016) [34]	12	1 W <sub>p</sub> /1 kW <sub>p</sub>	✓	✓	–/–	P	PI/IN	S	■	5	25/5	1300	75
PSC													
Celik et al. (2016) [35]	3	1 kWh	✓	✓	–/✓	P	IN	C	□	15	5	1700	75
Espinosa et al. (2015) [36]	2	1 kWh	✓	✓	✓/✓	C	L	C	□	11.5/15.4	1	1700	N/A
Gong et al. (2015) [37]	2	1 m <sup>2</sup>	✓	✓	–/–	P	PI/IN	M	■	9.1/11	2	1960	80
Serrano-Lujan et al. (2015) [38]	3	1 kWh	✓	✓	✓/✓	C	L	C	□/■	6.4–9.2	1	1700	80
Zhang et al. (2015) [39]	3	1 cm <sup>2</sup>	–	✓	✓/✓	C	L	S	□	6.5	N/A	N/A	N/A
Zhang et al. (2017) [40]	10	1 cm <sup>2</sup>	✓	✓	✓/✓	C	L	S	■	4.88–20.0	1	1700	75
QDPV													
Şengül et Theis (2011) [41]	1	1 m <sup>2</sup>	✓	✓	–/–	P	PI/IN	S	□	14	25	1700	80

<sup>a</sup> KEYIs: key indicators: FU: functional unit; CED: cumulative energy demand; GWP: global warming potential; RDPf: resource depletion, mineral, fossil, and renewable resources; Tox: one of the two toxicity indicators; ✓ considered in LCA datasets and compliant with the introduced KEYIs/ – not considered or not compliant; <sup>b</sup> KEYAs: key modeling assumptions: LCA type: C: conventional; P: prospective; TS: technology scale with options: L: laboratory scale; PI: pilot scale; IN: industrial scale; PS: considered product system with options: C: cell; M: module; S: system; SB: system boundaries with options: ■ downstream stage included/ □ only upstream stage; <sup>c</sup> Reviewed KEYPs: key performance parameters:  $\eta_R$ : efficiency;  $\tau_R$ : lifetime;  $PR_R$ : performance ratio;  $I_R$ : irradiation; DS: number of LCA data sets per study; N/A: data not available.

The systematic review of the KEYAs was conducted according to the four qualitative factors. None of the reviewed LCA studies reported the TRLs nor distinguished between conventional and prospective LCAs, since the latter distinction emerged recently in [51,52]. Therefore, the classification of LCA type and the technology scale was conducted based on keywords and data sources of the reviewed LCA datasets (see File S1, Supplementary Materials, for more information on this classification). In particular, for the LCA studies on PSC, based on primary data sources, specified keywords such as “laboratory production” [30], “laboratory-scale experiments” [39], and “pilot line facility” [27] allowed a clear classification of the technology scale and LCA type. In contrast, there were LCA studies based on secondary data sources and prospective assumptions on future development for which a clear classification of the technology scale was difficult, since the prospective assumptions were not specified in a transparent manner. Therefore, the classification of the upscaled technology scale was not clear. For these prospective LCA studies, the technology scale was not differentiated between pilot and industrial scale (PI/IN). The systematic review showed that OPV was mostly assessed by prospective LCAs (16 of 67 LCA datasets) or based on pilot- or industrial-scale manufacturing routes (35 of 67 LCA datasets). For PSC, only two LCA studies considered prospective assumptions, but most LCA datasets (18 of 23) were assessed based on the current laboratory scale, with the number of TRLs lower than four. The DSSC and QDPV datasets both came from prospective LCAs. Consequently, the assessed OPV was more mature than the other three emerging PVs considering the reviewed LCA datasets in this meta-analysis.

Regarding the considered product system, most LCA datasets on OPV considered PV modules and those on PSC considered PV systems. The latter is surprising since the PV system includes the BOS components that are highly dependent on the unknown future application of PSC. Consequently, this is a highly speculative assumption at this stage of development. The layer components of the reviewed LCA datasets are summarized in Table 1 (more detailed layer information per LCA dataset can be found in File S1, Supplementary Materials). Considering the system boundaries, the full life cycle was only assessed in two LCA studies. The downstream stage was only included in 27 of the 94 LCA datasets. In most LCA data sets, the focus lay in the upstream stage (47 of the 94 LCA datasets).

The systematic review on the KEYPs showed high variations, varying from too pessimistic to too optimistic, influenced by the KEYAs. The assumed efficiency of the reviewed LCA datasets ranged from 0.7% to 7.7% for OPV and from 4.88% to 20.0% for PSC. In spite of these high variations, it was observed that the efficiency of PSC was generally higher than OPV as confirmed in the literature [3]. However, the efficiency of OPV was assumed pessimistically considering the current maximum reported efficiency of 15.6%, trackable by the best research cell efficiency chart of the National Renewable Energy Laboratory (NREL) [3] or by the solar cell efficiency tables by [55]. The single values for DSSC and QDPV rather fell into the range of PSC efficiency, even though their current maximum reported efficiencies were in the range of the OPV maximum. Taking into account the KEYAs, the influence of the technology scale was low. Despite the low TRLs of PSC, they showed efficiencies in the range of first- and second-generation PVs. In contrast, the considered product system and the layer components had high influences on the reviewed efficiencies. Due to the larger active area of PV cells, they showed higher efficiencies than PV modules or PV systems. In contrast to the best reported ones, the efficiency of the PV cells was influenced strongly by the layer components and the included materials, e.g., the PSC with lead in the active layer showed generally higher efficiency than the one with tin. The system boundaries had no influence at all. The reviewed lifetimes varied for all four emerging PVs between one and 25 years. These figures should generally be rated as highly speculative assumptions due to the three reasons. Firstly, they cannot be proven by the maximum reported lifetimes. Secondly, low lifetime assumptions (1–2 years) result from the current state of research and are currently more realistic. Thirdly, the lifetime assumptions are not influenced by the choice of product systems, layer components, and system boundaries. The other two KEYPs, I and PR, were assumed as 1700 kWh/(m<sup>2</sup>·year) and 80% in almost all reviewed LCA datasets. The irradiation represents the average yearly solar energy achievable per m<sup>2</sup> and depends on the location of the operation stage of the PVs. The value of 1700 kWh/(m<sup>2</sup>·year)

was the typical value of southern Europe; however, in central Europe, lower values were obtainable, while higher values were obtainable in the southwestern part of the United States. The product of irradiation and efficiency specifies the direct current generated by the PV cell, module, or system. In contrast, the performance ratio indicates the share of the direct current that is finally fed into the grid as alternating current after deduction of the system-related losses. Eighty percent is the typically used value for ground-mounted systems [48]. Currently, even higher values of 90% are possible due to improvements in inverter efficiencies, as well as the design and maintenance of PV systems in recent years [48,56]. Both KEYPs were only relevant for the operation stage.

### 3.2. Harmonization of LCA Datasets on Emerging PVs

#### 3.2.1. Mathematical Procedure of the Harmonization

The progressive alignment of the KEYIs of each reviewed LCA dataset to the harmonized KEYIs was performed according to Equations (2)–(7), as given in Table 3. Due to the fact that different functional units were encountered in LCA studies, the calculation encompassed two steps. In the first step, the values of the KEYIs were converted to the functional unit of 1 m<sup>2</sup> according to Equation (2), which was independent of the dataset-specific KEYPs ( $\eta$ , PR, I,  $\tau$ ). For this conversion, three conversion factors depending on the functional unit of the reviewed LCA datasets were necessary (Equations (3)–(5)). As described before, the unit of areas was independent of the dataset-specific KEYPs; thus, the conversion factor was 1 (Equation (3)). In contrast to this, the units of power and energy were influenced by these KEYPs and, consequently, the conversion aimed for the mitigation of their influences by removing the dataset-specific information (Equations (4) and (5)). In the second step, the values per 1 m<sup>2</sup> were converted to the case-specific functional unit of 1 W<sub>p</sub> or 1 kWh by the use of standard values of  $\eta$ , PR, I, and  $\tau$  (see next section), as shown in Equations (6) and (7), respectively.

**Table 3.** Mathematical procedure of the extended harmonization approach of Equation (1) and the used standard values of the four KEYPs.

Harmonization Equations	Parameter/Units	Abbreviations	Standard Values
<b>Conversion of the reviewed KEYIs to W</b>			
$W = KEYI_R \cdot CF$ (2)	Total life-cycle impacts of the LCA dataset in LCIA/m <sup>2</sup>	W	-
	Reviewed key indicator in LCIA/FU	KEYI <sub>R</sub>	-
	Conversion factor	CF	see Equations (3)–(5)
<b>Conversion factors depending on the reviewed functional unit (FU)</b>			
$CF = 1$ (FU = 1 m <sup>2</sup> ) (3)			
$CF = E \cdot \eta_R$ (FU = 1 W <sub>p</sub> ) (4)	Light intensity in W/m <sup>2</sup> according to IEC 61215 [49]	E	1000
$CF = \eta_R \cdot PR_R \cdot I_R \cdot \tau_R$ (FU = 1 kWh) (5)	Reviewed KEYPs	$\eta_R, PR_R, I_R, \tau_R$	-
<b>Harmonization of the case "characterizing the status quo"</b>			
$KEYI_H = \frac{W}{E \cdot \eta_H}$ (6)	Harmonized key indicator in Case "status quo": LCIA/Wp Case "prospects": LCIA/kWh Standard values of the KEYPs: • efficiency in %	KEYI <sub>H</sub>  $\eta_H$	-  DSSC: 6 OPV/QDPV: 8 PSC: 12
<b>Harmonization of the case "possible future performance"</b>			
$KEYI_H = \frac{W}{\eta_H \cdot PR_H \cdot I_H \cdot \tau_H}$ (7)	• performance ratio in % • irradiation in kWh/(m <sup>2</sup> ·year) • lifetime in years	PR <sub>H</sub> I <sub>H</sub> $\tau_H$	80 1700 -

### 3.2.2. Standardization of the KEYPs

For the alignment of the harmonized KEYIs, the standard values of the four KEYPs were needed, i.e.,  $\eta_H$  as the percentage per module area  $A$  in  $m^2$ ,  $PR_H$  as a percentage,  $I_H$  in  $kWh/(m^2 \cdot year)$ , and  $\tau_H$  in years. The values were identified as described below.

In the case of efficiency  $\eta_H$ , the standardization was drawn on the reporting of progress and achievement of efficiency increase for the best PV research cells provided by [3] and [55]. Here, the emerging PVs were ranked from the highest to the lowest measured best cell efficiencies as follows: PSC (23.7%), QDPV (16.6%), OPV (15.6%), and DSSC (11.9%) [3]. To define a standard value of each emerging PV, the ratio of the best cell efficiencies to the harmonized module efficiencies of the first- and second-generation PVs in [11,12] was considered, which resulted in a ratio of 50% for all technologies (see Table S3, Supplementary Materials, for more information). The final standard values used for the harmonization of the four emerging PVs are given in Table 3. The values assume uniform efficiencies per emerging PV even though the emerging PVs might be further subdivided per morphology. To obtain the most promising morphology, i.e., most efficient and stable cells, using the bulk heterojunction approach was one of the biggest challenges of the current research [57–60]. To account for the variations in the efficiency assumptions depending on the morphology, a sensitivity analysis on the efficiency from 1% to 20% was conducted.

The irradiation  $I_H$  in  $kWh/(m^2 \cdot year)$ , performance ratio  $PR_H$  as a percentage of the PV system, and operating lifetime  $\tau_H$  in years were only needed for the case of a functional unit of 1 kWh of generated electricity. While  $I_H$  and  $PR_H$  are set to  $1700 kWh/(m^2 \cdot yr)$  and 80%, respectively, according to [11,12], where no standard value of  $\tau_H$  was defined. Due to the high uncertainty, the influence of the lifetime was assessed by means of sensitivity analysis. The sensitivity analysis covered the range of lifetimes from one year, which was the lowest estimate of studies and, thus, the worst-case assumption, to 30 years, which was the typical lifetime of first- and second-generation PV applications. It should be noted that the latter value is purely hypothetical at this stage of development and is only used for comparability reasons.

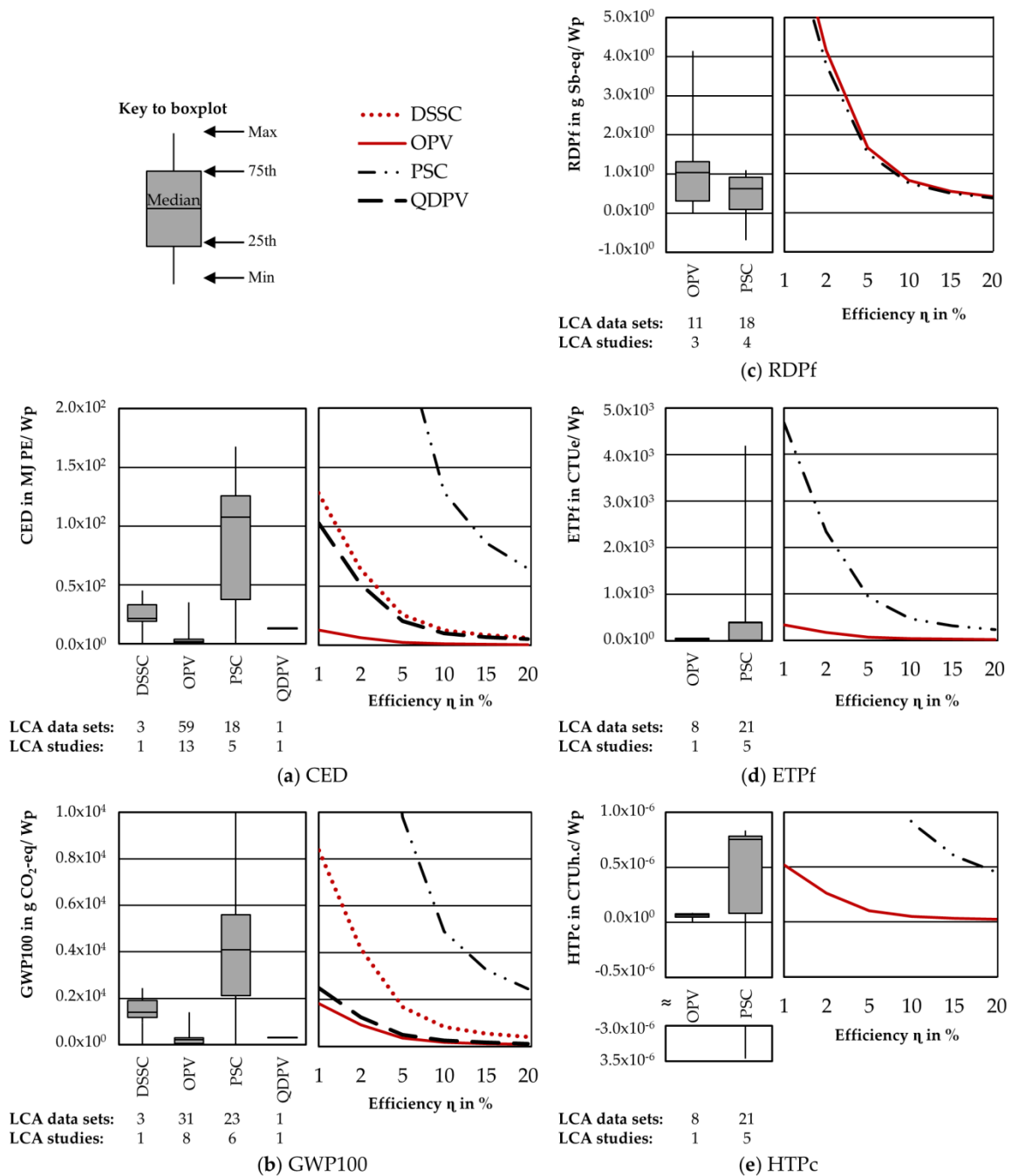
The two spreadsheet-based meta-models for the harmonization of the KEYIs using these standard values of the KEYPs can be found in File S1 (Supplementary Materials).

### 3.3. Status Quo of the Environmental Performance of Emerging PVs

The environmental status quo was evaluated based on the median and the interquartile range (IQR) (75th minus 25th). For OPV and PSC, as a result of harmonization, the IQR distributions decreased for all KEYIs. For the medians and the other two emerging PVs, there was no clear finding. Here, the medians decreased for all KEYIs in the case of OPV and only for CED and GWP in the case of PSC, since the standardized  $\eta_H$  values were higher than the assumptions of the reviewed LCA datasets. In contrast, the medians of the other KEYIs increased due to higher efficiency assumptions. For DSSC and QDPV, the single values for the two KEYIs, CED and GWP, increased as well due to the high speculative assumed efficiencies of their reviewed LCA datasets. Overall, there was a correlation between CED and GWP; both medians decreased by about 60% for OPV and by about 10% for PSC, as well as increased by about 30% for DSSC and by 75% for QDPV. The rationale behind the correlation was that the energy demand was still covered to a large extent by fossil fuels, responsible for large extents of GHG emissions and, consequently, for high GWP impacts. For the other three KEYIs, no quantifiable correlation was identified at this point (see Table S4, Supplementary Materials).

In Figure 2, the results of the environmental status quo are presented as boxplots of the five harmonized KEYIs, indicating the median, IQR, and the minimum and maximum values. In order to depict the influence of the standardized efficiencies  $\eta_H$ , the results of the sensitivity analysis of the median are included in Figure 2. For the discussion of the results, three premises were used. Firstly, as the median of each KEYI decreased, so did the life-cycle impacts that occurred, together with an improvement in the environmental performance. Secondly, as the IQR decreased, the harmonized KEYIs became more robust; however, here, the number of studies was taken into account since a small

IQR resulting from a small number of datasets, possibly from one study with common assumptions, may have been subject to uncertainties. Thirdly, a sharper decrease in the median for the sensitivity analysis resulted in a stronger influence of the efficiency on the result.



**Figure 2.** Current environmental status quo. Boxplots of the five key indicators (KEYIs) harmonized to the consistent functional unit of 1  $W_p$  and standard values of the efficiencies (Table 3) (left), as well as influence of the efficiency range (1–20%) on the medians (right).

For CED and GWP, the best environmental performance in terms of the lowest and most robust results was found for OPV: 2 MJ PE/ $W_p$  and 228 g  $CO_2$ -eq/ $W_p$ , respectively. The highest and least robust results were indicated for PSC, with the lowest results in the range of the OPV median and the highest results over 100-fold higher. Both findings were based on a substantial number of LCA studies (between five and 13 studies, providing between 18 and 59 datasets). For DSSC and QDPV,



only CED and GWP were assessed. Both KEYIs were higher than OPV but lower than PSC. However, the findings on DSSC and QDPV were limited to a single LCA study, including three or fewer LCA datasets. In contrast to OPV, the medians of both KEYIs decreased sharply with increasing efficiency for PSC, DSSC, and QDPV. However, DSSC and QDPV came close to the OPV values in the case of an efficiency of 20%, but there was still a wide gap with PSC. Accordingly, the results of PSC, DSSC, and QDPV were highly influenced by efficiency increase.

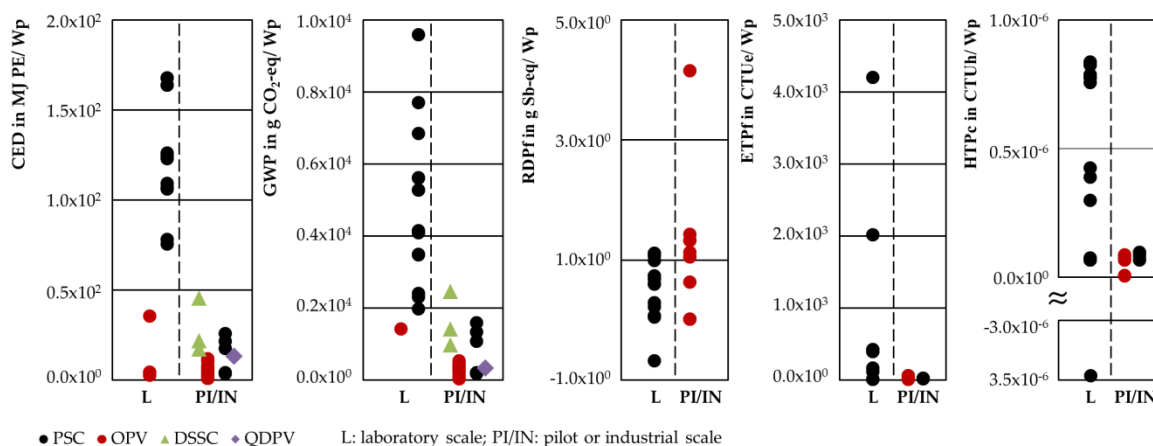
For the other three KEYIs, RDPf, ETPf, and HTPc, results were only available for OPV and PSC. Here, OPV again performed better than PSC for the two toxicity indicators, although it should be noted that this finding resulted from only one LCA study providing eight LCA datasets with similar assumptions; thus, little to no deviations existed. The boxplots and sensitivity analyses showed similar curves for the toxicity indicators compared with CED and GWP. Even though there was no quantifiable correlation between the CED and the two toxicity indicators, there was an apparent dependency. Contrary to this, the results indicated that there was no correlation at all between the CED and the related high fossil fuel share and RDPf. The medians of RDPf, resulting from three and four LCA studies with 11 and 18 LCA datasets, were similar to OPV and PSC, with a slightly higher value for OPV. Although fossil fuels and mineral resources were included in RDPf, this KEYI was more influenced by the mineral resources due to their higher characterization factors. However, the characterization factors of silver and gold as the most used materials of the back electrode of OPV and PSC were over 8 kg Sb-eq/kg; for fossil fuels, they were less than  $1.0 \times 10^{-7}$  kg Sb-eq/kg. The sensitivity analysis also showed that both emerging PVs had similar curves. However, considering, in general, the higher efficiency of PSC, PSC performed better than OPV for RDPf. Accordingly, there was no shift in negative environmental impacts from the energy-related and material-related KEYIs and, consequently, no tradeoffs were expected.

For an in-depth interpretation of the results, the influences of the KEYAs on the KEYIs and the tradeoffs occurring during the life cycle of PVs were evaluated. The evaluation was based on the single included LCA datasets and the single options of the KEYAs, which were laboratory vs. pilot/industrial for the technology scale, PV cell vs. PV module/system for the considered product system, and upstream vs. downstream impacts for the system boundary.

Regarding technology scale, the pilot or industrial scale was obviously predominated by the OPV dataset results, while, in the case of PSC, the majority of LCA datasets were distributed to the laboratory scale. For PSC, this difference in the technology scale resulted in both higher values and a larger distribution of PSC results compared with OPV, in particular for the three following KEYIs: CED, GWP, and HTPc (Figure 3). The reasons for this might have been the influence of the technology scale and tradeoffs resulting from the layer materials and deposition methods used in laboratories and might not have resulted from tradeoffs during the life cycle, indicated by the considered product system or system boundaries. In order to verify this finding, disaggregated information on each layer of the PSC cells was evaluated. The evaluation indicated three kinds of tradeoffs originating from the layer materials and deposition methods, as discussed below.

Firstly, the selection of layer materials influences the environmental performance of each layer and is expected to be different for industrial and laboratory productions. For example, for PVs, gold, as the typically used material for the back electrode on the laboratory scale, has a much higher impact than silver and aluminum used on the pilot or industrial scale [35–37,40]. Secondly, in the laboratory, the thickness of a layer is not of great relevance and often not measured, so more material than necessary for the optimal performance is used. Thirdly, energy-inefficient deposition methods are applied on the laboratory scale compared with the pilot or industrial scale. Several publications support this finding, e.g., the CED of the back electrode was reduced by six-fold from the laboratory deposition of gold by thermal evaporation (36 MJ PE/W<sub>p</sub>) [40] to the industrial scale in which gold was substituted by C-paste and deposited by spray coating (4 MJ PE/W<sub>p</sub>) [35]. For the active layer, even higher reductions of up to 15-fold were reported. Similar results were observed for OPV development. Starting with a CED of 47 MJ PE/W<sub>p</sub> for manufacturing an OPV cell on the laboratory scale, including

typical laboratory manufacturing surroundings such as a nitrogen atmosphere and deposition methods such as spin-coating and annealing for depositing the active layer and thermal evaporation for the electrodes [33], the CED was reduced significantly to 6.3 MJ PE/W<sub>p</sub> [23] and 0.7 MJ PE/W<sub>p</sub> [32] by enhancing the PV cell manufacturing to roll-to-roll production with the deposition method of slot die coating and screen printing without nitrogen atmosphere.



**Figure 3.** Influence of the technology scale and their single values, laboratory (L) vs. pilot/industrial (PI/IN) scale, on the single harmonized life-cycle assessment (LCA) dataset points of the five KEYIs.

For the considered product system, no influence could be determined due to the limited number of LCA datasets reporting the contributions of the additional components of the PV modules, the encapsulation, and the PV system (the BOS). Nonetheless, for PSC only, three LCA studies enabled the consideration of the additional components. However, in contrast to the literature [50], no tradeoffs of the additional components could be determined since their contributions were less than 5% [37,39,40]. This might be explained by the high impacts resulting from the production of the PSC cells compared with the small contributions of the additional components. For the other three emerging PVs with lower impacts, the additional components, especially the BOS, showed high contributions to all five KEYIs, ranging from 11% to 48% [50].

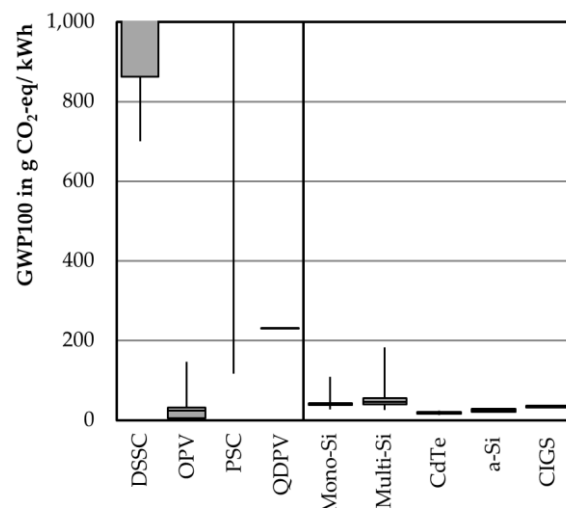
Regarding system boundaries, in the case of the status quo analysis, the operation phase was excluded by definition, and the only two possible options were the upstream stage and the combination of up- and downstream stage. The inclusion of the downstream stage led to a rather minor increase in results for CED. However, the influence of the downstream stage on CED was negligible compared with the upstream impacts, since the impacts were less than 5% in the case of landfill as end-of-life treatment and even lower in the case of incineration [37,40]; this mattered for the other four KEYIs. In particular, for ETPf, there were two outliers (2000 CTUe/W<sub>p</sub> and 4200 CTUe/W<sub>p</sub>). Looking only at the downstream stage, the different choices of end-of-life treatment led to higher differences in the KEYIs. Landfill and incineration without lead recycling, had higher impacts with respect to HTPc and ETPf. Particularly, for ETPf, landfill as end-of-life treatment significantly increased the toxicity potential due to the released lead to the environment [38]. Incineration with lead recycling showed less impacts compared with landfill for ETPf and even negative impacts for HTPc and RDPf [38]. Except for ETPf, the influence and tradeoffs of the end-of-life treatment were minor compared with the high upstream impacts of the manufacturing in laboratories.

### 3.4. Future Prospects of Emerging PVs

For the assessment of future prospects of environmental performance, in the first step, the status quo of emerging PVs was contrasted with commercial first- and second-generation PVs, thus providing a benchmark for the technological development of emerging PVs. In the second step, the possible contribution of environmental performance resulting from changes in the most influencing factors,

including efficiency, lifetime, and upscaling of production, by means of sensitivity and scenario analyses, was assessed.

The conversion of the KEYIs to the functional unit of 1 kWh was based on the consistent KEYPs ( $\eta_H$ ,  $PR_H$ ,  $I_H$ ), given in Table 3. To depict the current state of development as the basis of the sensitivity analysis, the maximum reported lifetimes of seven years for OPV [46] and one year for PSC and QDPV were used [44,61]. For DSSC, no lifetime assumptions were found; thus, one year was used as well. As benchmarks representing the two first-generation PVs, monocrystalline silicon (Mono-Si) and multicrystalline silicon (Multi-Si), the harmonized results of Hsu et al. [11] were applied; also, for the three second-generation PVs, amorphous silicon (a-Si), cadmium–telluride solar cells (CdTe), and copper–indium–gallium–diselenide solar cells (CIGS), the results of Kim et al. [12] were applied. As both studies reported only results for GWP, the comparison with commercial PVs was limited to this KEYI. In Figure 4, the results of this comparison are presented as boxplots of each PV technology; insights into the other KEYIs can be drawn from the results of the status quo. OPV is the only emerging PV that presently meets the benchmark of the commercial technologies, although OPV has only a seven-year lifetime compared with the 30 years of commercial PVs. The median of OPV was in a similar range to CdTe, the commercial PV with the lowest GWP impacts. The other PVs were 5–70-fold higher than the commercial benchmarks.

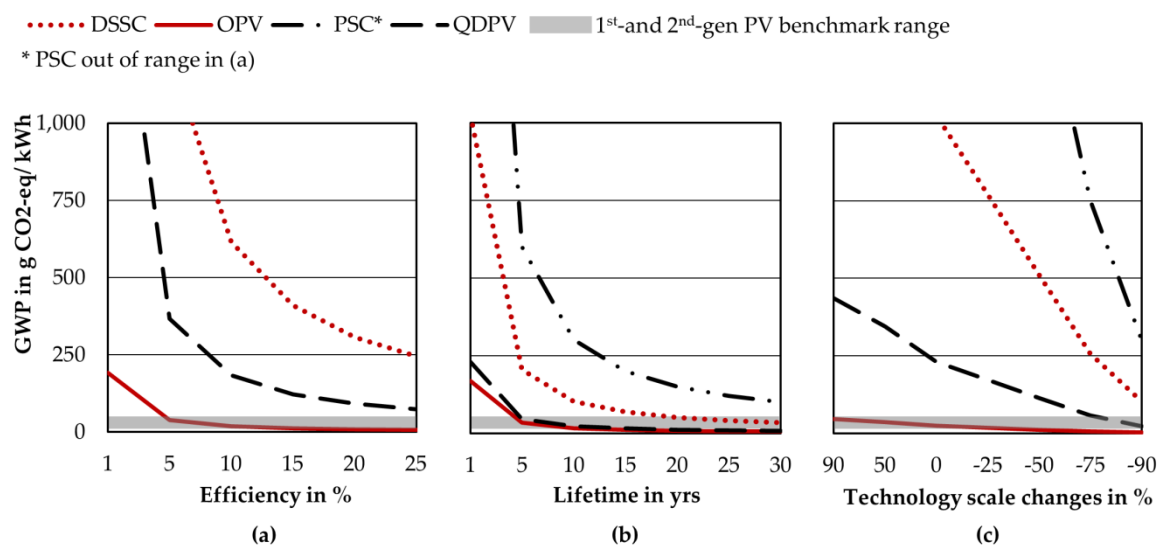


**Figure 4.** Global warming potential (GWP) status quo of current development of emerging PVs as presented in the LCA datasets and harmonized to the key performance parameters (KEYPs) in Table 3 and current maximum reported lifetimes of one and seven years. The comparison was based on benchmarks of the first- and second-generation PVs based on the standard values of the KEYPs ( $I_H = 1700 \text{ kWh}/(\text{m}^2 \cdot \text{year})$ ;  $PR_H = 80\%$ ;  $\tau_H = 30 \text{ years}$ ; Mono-Si:  $\eta_H = 13\%$ ; Multi-Si:  $\eta_H = 12.3\%$ ; CdTe:  $\eta_H = 10.9\%$ ; a-Si:  $\eta_H = 6.3\%$ ; CIGS:  $\eta_H = 11.5\%$ ) taken from References [11,12].

To analyze the influence of development on the efficiency, lifetime, and upscaling, the following assumptions for the sensitivity analyses were made:

1. Efficiency increase from 1% to 25% (the latter value was set as the most optimistic assumption based on the maximum reported efficiency [3]);
2. Lifetime increase from the minimum reported lifetime of one year to the most optimistic assumption of 30 years as the typical lifetime of first- and second-generation PVs;
3. Upscaling of production from the laboratory to industrial scale was depicted as changes in the energy demand from  $-90\%$  to  $90\%$  (as a proxy of the environmental impact in general) and, consequently, of the GWP impacts in the same range as a consequence of this technology scale leap.

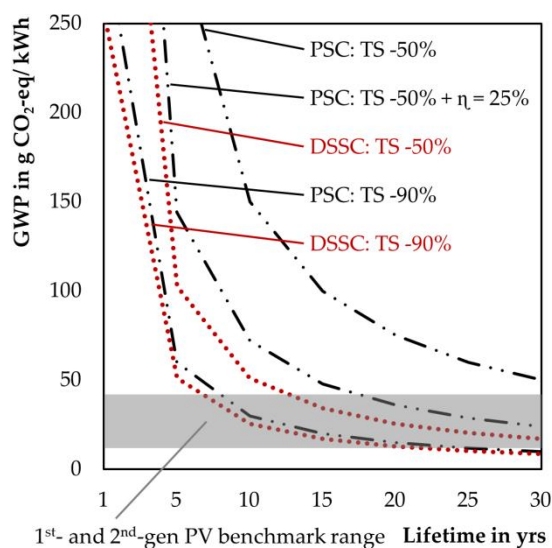
The results of the three sensitivity analyses are presented in Figure 5. The efficiency increase had the lowest influence. An efficiency increase would achieve lower results for OPV than for CdTe, but for PSC, an increase to 25% would result in 40-fold higher GWP than Multi-Si, the most common commercial PV with the highest GWP impact of 47 g CO<sub>2</sub>-eq/kWh. DSSC and QDPV showed values that were many times more than the commercial PVs as well. The lifetime increase to 30 years showed the highest contributions to GWP reduction. For OPV, the GWP could be decreased to 29% of CdTe and even 12% of Multi-Si; for PSC, the GWP was still higher but could be decreased to twice the Multi-Si impact. DSSC and QDPV were in the range of the benchmarks after lifetime increases to 20 and five years, respectively. The change in technology scale with stagnation of lifetime would result only in competitive GWPs for OPV, by an increase of 90% of the GWP impacts, and for QDPV, by reductions of 90%. Considering that GWP correlated directly to the energy demand, a reduction by 90% of the energy demand resulted in a reduction of 90% of the GWP impact.



**Figure 5.** Sensitivity analyses of the prospective development of (a) efficiency, (b) lifetime, and (c) upscaling of the four emerging PVs compared with the range of the benchmarks.

In particular, for PSC and DSSC, combinations of improvement of the influencing factors in order to reach the benchmarks were needed. In Figure 6, the most promising combinations are presented as scenario analyses of lifetime increase combined with efficiency increase and upscaling reduction. Based on this, PSC would need a 90% reduction and a five-year lifetime, only a 50% reduction but a lifetime of 30 years, or a lifetime of 15 years and an efficiency of 20%. The scenario analyses of the other combinations were not as promising; they can be found in Figure S1 (Supplementary Materials). Although the reduction of 90% is on one hand, arbitrary and not substantiated by a specific study, the review of the literature indicated that this is an optimistic but realistic assumption due to the expected improvements from laboratory to industrial scale regarding the material selection, material quantities, and efficiency of deposition methods.

Based on the insights from the status quo analysis, the behavior of the material-related KEYIs was quantitatively envisaged. They are expected to behave similarly to CED and GWP regarding lifetime and efficiency changes, since this behavior is described based on Equation (7). Accordingly, no tradeoffs were expected from these factors. In contrast to this, the KEYIs would behave differently regarding upscaling and change in energy demands. In particular, for RDPf, no significant changes would be expected from a decrease in energy demand during production due to the low contribution of the energy-related fossil fuel resources to this KEYI. For the other two KEYIs (HTPc and ETPf), lower energy demands would be expected to result in reductions, even if not to the same extent as for GWP. Here, tradeoffs between life cycle stages might be expected. The reduction of the upstream impact might result in increasing contributions of the downstream impact.



**Figure 6.** Summary of the scenario analyses of the three influencing factors, efficiency, lifetime, and upscaling, for perovskite solar cells (PSC) and dye-sensitized solar cells (DSSC); the single-scenario analyses of each combination of the influencing factors are given in Figure S2 (Supplementary Materials).

#### 4. Discussion

The environmental performance of emerging PVs was investigated based on a meta-analysis, including a systematic review and harmonization approach of 94 LCA datasets on DSSC, OPV, PSC, and QDPV. The systematic review showed that the definitions of the KEYPs, as well as the KEYAs, especially the technology scale, were not reported and explained sufficiently. For transparency reasons, the report of these values and the classification of the technology scale are highly recommended. The benefits of the harmonization approach are twofold. Firstly, it reduces the deviations of LCA results through the use of standard values of the KEYPs. Secondly, the alignment of LCA results to two alternative functional units enables a substantiated discussion of the environmental performance of emerging PVs for the two cases of status quo and future prospects. The status quo encompasses technology scales from the early laboratory state; here, the functional unit of  $1 W_p$  restricted the comparison of the material-related property related information of PV only to the industrial manufacturing scale. Here, in contrast, the functional unit of  $1 kWh$  included additional information on the application by integrating the lifetime into the comparison. Thus, a comparison of emerging to commercial technologies was feasible in view of identifying benchmarks of environmental performance; based on these benchmarks, the high uncertainty as to a future use phase was tackled by means of sensitivity analysis, leading to a scenario approach for different strategies of further technology development.

The analysis of the status quo based on the harmonized KEYIs showed the differences between the four assessed emerging PVs in terms of the median and IQR. In general, it should be noted that, for DSSC and QDPV, only a very limited number of LCA datasets were available, which generally restricted the validity of conclusions for these two technologies. For OPV, which was based on 67 LCA datasets, by far the lowest values for the median, i.e., best environmental performance, were found for all KEYIs except for resource depletion, RDPf, where the difference to PSC was low. Also, IQR was by far the lowest for OPV. The analysis of the KEYAs confirmed that these findings stood for a rather mature technology from the environmental perspective that is ready to enter the market; the good environmental performance could be mostly attributed to the low impact from production and less to the efficiency. On the contrary, for PSC, a far higher median was found; also, after harmonization, high deviations of results depicted a large IQR. As the functional unit of  $1 W_p$  represented the material-related properties of the PV only, the reasons for these results may have come from two contributions: the kind of layer material and the energy demand of the layer deposition, i.e., the stage of technology development. The KEYAs and an in-depth analysis of the underlying LCA studies

confirmed the high share of LCA datasets that were based on the early stage of development, associated with inefficient manufacturing methods of laboratory components and, thus, high energy demand. RDPf was the only KEYI not influenced by high energy demand and, for which, PSC could keep up at the current stage of development with OPV due to its higher efficiency. Based only on the material, the downstream phase could also be investigated as part of the status quo analysis. Based on the assumption of an advanced waste management, the influence of end-of-life treatment in general was low compared with the upstream impact.

For the analysis of future prospects, the use phase was included as additional information, notably the lifetime of the respective emerging PV. Based on the results of the current stage of development and assumptions on lifetime from the literature, the comparison with commercial PVs of the first- and second-generation PVs showed that, currently, OPV is the only emerging PV that can compete with commercial PVs, which was in line with the earlier finding that, out of the four investigated technologies, OPV is the only mature one. The future prospects of the other three technologies could be explored by sensitivity analysis of the three influencing factors of efficiency, lifetime, and upscaling; for the latter, the energy demand was used as a proxy for environmental impact in general. The results of the sensitivity analysis showed that efficiency increase had the lowest influence. Consequently, enhancement of efficiency alone could not make any of the three emerging technologies competitive with respect to the environmental performance of commercial PVs. Lifetime and energy efficiency had a greater influence and might be important, notably for DSSC, QDPV, and PSC. In general, a combination of improvements in each of the three influencing factors would be the most promising way to competitiveness. For this, the sensitivity analysis could be widened to a scenario analysis in order to identify successful combinations of improvements, where each contribution could be substantiated by the current state of evidence from the laboratory. This was explored in detail for PSC and DSSC. Current LCA results confirmed that considerable potential for improvement lies in the combination of a lifetime increase from five to 30 years and upscaling to the industrial scale, with expected reductions of more than 90%.

## 5. Conclusions

The application of LCA for emerging technologies has contradictory requirements. On one hand, the room for maneuvering in terms of freedom of design is largest in the early stages of technology development, which calls for a very early application in support of the development process. On the other hand, uncertainty of data for the technology alternatives for the future use phase compromises the usefulness of results from LCA for decision support. The developed harmonization approach for emerging PV presents a structured way not only to reduce uncertainty but also to extract significant information from the point of view of different stages of technology development. For the status quo analysis, information was reduced to the material-related properties, thus removing the high uncertainties resulting from assumptions of the future use phase. For the analysis of future prospects, the uncertainty of the use phase was handled by means of sensitivity and scenario analyses, where comparison with commercial PVs had the function of a benchmark that could be used for analysis of the current stage and strategies of technology development.

The important findings for the status quo concerned the characterization of the differences between PV technologies related to their selected materials and their current stage of development. The harmonized KEYIs showed important differences between technologies, and also within the technology of PSC, which could be attributed to the underlying material systems. Conclusions from the analysis of these differences were twofold. Firstly, possible tradeoffs between impact categories, notably those related to energy and those related to toxicity, were not as relevant as might have been expected. An important caveat is that this conclusion was based on a future end-of-life phase that met the requirement of a state-of-the-art waste management system, ensuring sound management of toxic compounds of PV materials. Interestingly, a positive contribution from the end-of-life phase to the environmental performance of emerging PVs could possibly be envisaged from advanced recycling



technologies for materials that are currently not well developed and, thus, not reflected by LCA studies. Secondly, a significant influence of different material systems can be seen for the energy-related KEYIs, which resulted from the interdependence of selected material system and layer manufacturing techniques. The latter indicated the high contribution of inefficient laboratory manufacturing to the status quo performance of emerging PV. Future LCAs could be supported by a more in-depth investigation of upscaling, yielding information on methods, materials, and cell configurations of industrial manufacturing.

The investigation of future performance of emerging PVs showed that, to meet today's technology benchmarks, a combination of improvements in the factors of lifetime and upscaling would be most promising for PSC. OPV already meets the performance level with respect to KEYIs per kWh of today's best technologies. However, the low efficiency and the related high demand of area in combination with the still low lifetime of far below 20 years hinders its application as a surrogate of today's roof application. In the case of PSC, energy savings from upscaling, as well as the possible lifetime, are crucial factors for application. Current studies gave evidence that, for PSC, an increased environmental performance from upscaling can be expected with a high probability. Regarding possible lifetimes of PSC in real world conditions, until now, no reliable statement can be made. However, if the challenge of a high lifetime can be managed successfully by technology improvement, in view of the already high efficiency, this technology might be a future substitute or supplement for roof application, competing with or even exceeding the performance of today's PVs. Here, one development went for tandem application with enhanced efficiencies [3,62,63]. With respect to the other two emerging PVs, DSSC and QDPV, as of now, the available literature is too small to draw conclusions for future prospects.

As a general conclusion regarding LCA studies on emerging technologies, these insights point to the importance of the intended application of a technology that received little attention in LCA studies for PVs until now. Most current studies implicitly assumed that emerging PVs will substitute existing ones or other electricity generation technologies feeding the grid. However, due to their novel properties, emerging PVs might have many other applications even at shorter lifetimes than today's PVs, such as small devices, e.g., mobile chargers, lamps, clothes, and other gadgets. Due to the change in intended application, other benchmarks for technology development and comparisons of the environmental performance need to be considered for these devices. As a first example, in [64] an LCA of a mobile charger with an integrated OPV cell was performed and the environmental performance in comparison with substituted electricity from the grid as a benchmark was analyzed. Obviously, for such novel applications, behavioral aspects in the use phase, as well as different requirements for the end-of-life management, might substantially influence environmental performance in the life cycle [64]. Thus, for a comprehensive picture of future environmental performance of emerging technologies, not only the technology itself but also emerging applications of technologies should be considered in LCA studies.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/1996-1073/12/22/4228/s1>: Table S1: Keywords and synonyms of the database search; Table S2: Overview of the excluded LCA datasets per collected LCA study after the secondary screening; Table S3: Ratio between best research cell efficiencies and standard values of first- and second-generation PVs; Table S4: Comparison of the descriptive statistics of the KEYIs harmonized to the consistent functional unit of 1 W<sub>p</sub> and after full harmonization (including the standard values of the efficiency), subdivided by the five KEYIs; Figure S1: Influence of the KEYAs on the single harmonized LCA dataset points of the five KEYIs (a) technology scale (laboratory (L) vs. pilot/industrial (PI/IN)); (b) product system (cell (C) vs. module/system (M/S)); (c) system boundaries (cradle-to-gate (Gate) vs. cradle-to-grave (Grave)); Figure S2: Detailed scenario analyses of the three influencing factors, efficiency, lifetime, and upscaling, for PSC and DSSC; File S1: Supplementary meta-analysis results.

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## Nomenclature

<b>PVs</b>	<b>Photovoltaic technologies</b>
Mono-Si	Monocrystalline silicon
Multi-Si	Multicrystalline silicon
a-Si	Amorphous silicon
CdTe	Cadmium–telluride solar cells
CIGS	Copper–indium–gallium–diselenide solar cells
CZTSSe	Copper–zinc–tin–sulfur–selenide solar cell
DSSC	Dye-sensitized solar cell
OPV	Organic photovoltaic
PSC	Perovskite solar cell
QDPV	Quantum-dot photovoltaic
<b>KEYIs</b>	<b>Key indicators</b>
CED	Cumulative energy demand in MJ PE (primary energy)
ETPf	Ecotoxicity potential for freshwater in CTUe (comparative toxic units for ecosystems)
GHG/GWP	Greenhouse gas/global warming potential in g CO <sub>2</sub> -eq (carbon dioxide equivalents)
HTPc	Human toxicity, cancer effects in CTUh (comparative toxic units for human health impacts equivalent to incidence of cancer)
RDPf	Resource depletion, mineral, fossil, and renewable resources in g Sb-eq (antimony equivalents)
<b>KEYAs</b>	<b>Key modeling assumptions</b>
C	Conventional
P	Prospective
TS/TRL	Technology scale/technology readiness level
L	Laboratory scale
PI/IN	Pilot/industrial scale
<b>KEYPs</b>	<b>Key performance parameters</b>
$\eta$	Efficiency
$\tau$	Lifetime
I	Irradiation
PR	Performance ratio
<b>Further</b>	
BOS	Balance-of-system
LCA	Life-cycle assessment
W <sub>p</sub>	Watt-peak

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